COSMOLOGY OF OUR UNIVERSE

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ABSTRACT

In this paper we review the present status of cosmology. First we stress the applicability of laboratory tested physical laws to the study of our Universe by giving examples of extremely accurate laws of physics. Second we review the astronomical information regarding the large scale structure of our Universe. From this information the Einstein-Friedmann cosmology is developed. Next we describe the physical processes that take place during the evolution of our Universe. We then describe how cosmological theories can be tested by observing the remnants of creation of our Universe and by observing the large scale structure of our Universe (such as the 3 °K cosmic radio spectrum). It appears that our Universe can be described by the open model of the big bang theory.

Introduction

Man has long sought to know the past as well as the future course of evolution of his Universe, but only in recent years has he succeeded in even partially understanding how it originated. And although he cannot yet predict the nature of the Universe with confidence, he now knows how to proceed to learn about its course of evolution.

Cosmology, like all sciences, must be based on observational or experimental data. Unfortunately, until recently, observational data relevant to cosmological theories were virtually nonexistent. In the absence of data, cosmology had become the hunting ground of speculators. Some theories were based on hypothetical assumptions concerning a small violation of physical laws (such as energy nonconservation or the inequality of proton electron charges); others were based on cosmological principles imposed by man. Interesting as these theories may be, they have contributed little to an understanding of the actual course of evolution of the Universe.

Cosmology should be regarded as a branch of physics and hence subject to the laws of physics. Speculations should be verifiable in the laboratory of physics. Because we are dealing with cosmological scales (of a time duration in the order of ten billion years, or of a spatial extension of the dimension of 10^{28} cm), one may argue that laws verified in the laboratory may not be applicable to the Universe, and that one must invent different laws. This approach is incorrect. Evidence shows that some well-established physical laws are clearly applicable to the Universe.

Because of galactic rotation and the relative motion of the sun with respect to other stars, in the course of a human life span (say, 70 years) we will have sampled a volume of space $10^{17} \times 10^{15} \times 10^{15}$ cm^3. The time span would be on the order of 2×10^9 sec. Suppose a physical constant (such as the electron charge e, or the gravitational constant G) changes with respect to other physical constants (such as the Planck's constant h etc.) in the course of evolution of our Universe. Suppose its magnitude has changed by a factor of two in the life span of our Universe (in the order of 10^{18} seconds). Then if we can perform an experiment to an accuracy of 10^{10}, we can already determine whether this physical constant (such as the electric charge e, gravitational constant G, etc.) has actually changed by a factor of two over the age of the Universe. Such an accuracy is not totally beyond our capability. In fact, a number of experiments giving an accuracy much higher than one part in 10^{10} have been performed. Several examples of this type of precise experiment are given below:

1. <u>The equality of electron and proton charge</u>. It is generally accepted that atoms are neutral. To what degree is an atom neutral? In an atomic beam experiment, Vernon W. Hughes of Yale University discovered that any difference between the charge of electrons and the charge of the nucleus had to be

less than one part in 10^{21}. Thus, in practice, atoms can be taken to be strictly neutral.

2. Lorentz invariance of charge. Does the charge of an electron depend on its velocity? In Hughes' experiment, several types of atoms were used with orbital velocities of the electrons ranging from 10^{-3} c (c = light velocity) to 0.1 c. From his experiment it may be concluded that the electric charge stays constant to one part in 10^{17} for electrons with velocities up to 0.1 c.

3. Isotropy of the inertia mass. It has been accepted that the property of mass is isotropy, that is, under the action a gravitational field (or other fields) the acceleration of a mass is independent of its direction in the Universe. To what extent is this true? Vernon W. Hughes again showed that mass is strictly isotropic to an accuracy of one part in 10^{22}.

4. Longevity of the protons. It is accepted that protons are stable. But how stable are they? Frederick Reines discovered that if protons were unstable, their lifetime against all possible modes of decay must exceed 10^{26} years. This is many times greater than the age of the Universe, which is 10^{10} years.

5. Variation of the gravitational constant. Robert H. Dicke and his associates at Princeton University have shown that the gravitational constant is constant (as measured against the electromagnetic interaction) to one part in 10^9 over a period of one year. If Dicke can extend his measurement to

two or more powers of ten, then the crucial question as to whether the gravitational constant is constant over the life span of the Universe can be answered.

6. Variation of the electric charge. Dyson has pointed out that the electric charge cannot vary (with respect to the nuclear interaction strength) by more than one percent during the entire life span of the Universe.

These examples serve to illustrate that physical laws established in laboratories are applicable over cosmological scales.

If we accept the fact that cosmology is a part of physics, then we must also accept the fact that, like other branches of physics, cosmology must be modified from time to time. There is no such thing as a "final theory of our Universe." In a sense, cosmology will lose its magic of reverence — a cosmologist can no longer create a Universe by pencil and paper alone. In another sense, a cosmological theory may now be formulated which is based on meaningful physics.

This is the approach that I believe a modern cosmologist should take, and it is the one which I have adopted in this article.

Our Astronomical Universe.

The basic constituents of the Universe are the five fundamental particles: protons, neutrons, electrons, photons, and neutrinos. Neutrinos are ashes from nuclear fires in stars;

they are not found in ordinary matter. The other particles make up the nucleus and atom, glued together by the nuclear force and the electromagnetic force to form ordinary matter. Large collections of matter are held together by gravity to form stars and galaxies. Astronomically, galaxies can be detected over distance on the cosmological scale. (Galaxies are also bound by gravitational forces to form clusters of galaxies; however, clusters of galaxies are not as densely packed as stars in galaxies.) In cosmological theory it is convenient to regard galaxies as the basic elements of the Universe.

Galaxies contain from 10^5 to 10^{12} stars; most contain 10^{11} stars. The average mass of a star is close to one solar mass, hence the average mass of a galaxy is 10^{44} grams.

The distribution of galaxies is generally uniform up to a distance of 2×10^9 light years (one light year = 9×10^{17} cm), with a variation of a few percent. In general, the distribution is isotropic and homogeneous to a distance of 2×10^9 light years. The matter density due to galaxies, according to Oort, is 3×10^{-31} grams per cubic centimeter. The average distance between two neighboring galaxies is one to two million light years.

The most important question to ask is: How are astronomical distances determined over the cosmological scale? The answer involves two steps of extrapolation.

Certain stars, called variables, are found to vary in their light output. In 1912 Miss Leavitt discovered a definite relationship between their luminosity (intrinsic brightness) and their period of variation. Therefore, if the period is known, the total intrinsic brightness can be determined; by comparing the total energy output with the apparent brightness of variable stars, one can determine the distance. The one variable that is most useful in cosmological research is the Cepheid or classical variable. Its period ranges from 1 to 100 days and its luminosity is in the range 10^4 to 10^5 solar luminosity (solar luminosity = 4×10^{33} ergs/sec). Because of the high luminosity of these variables, they can be photographed even in galaxies at distances as far as 10^7 light years.

Using this method, Hubble in 1925 determined the distance of a number of nearby galaxies, up to a distance of 10^7 light years. A few years earlier, some astronomers had already found that external galaxies possess enormous receding velocities up to 1000 km/sec. Hubble discovered that a linear relationship exists between the receding velocity (determined by the shift of two calcium absorption lines - H and K, and the distance). The red shift is the shift of spectrum lines toward the longer wavelength. It is defined by

$$z = \frac{\Delta\lambda}{\lambda} \left(\cong \frac{v}{c} \text{ if velocity is small}\right)$$

where λ is the original wavelength and $\Delta\lambda$ is the difference between the shifted wavelength and the original wavelength λ. The distance is determined from the Cepheids that Hubble resolved at the arms of these galaxies. This relation takes the following form:

$$\text{velocity } (V) = H_o \text{ times distance } (R)$$

or

$$V = H_o R$$

R is the distance and H_o is a constant (called Hubble's constant). The most recent value of H_o is

$$H_o = 100 \text{ km/sec/megaparsec} = 1/3 \times 10^{17} \text{ sec.}$$

(megaparsec = one million parsec; parsec = parallax of one second of arc = 3.26 light years). Thus, the receding velocity is 100 km/sec if the distance is 3.26 million light years.

The equation $V = H_o R$ certainly fails for distances whichgive a value of V greater than or equal to c, the velocity of light. It has been verified to distances for which V = 0.2 c, for which the distance R is in the neighborhood of 2×10^9 light years.

If the curvature effect is neglected, then the inverse square law should be valid:

$$f = \frac{F}{4\pi R^2}$$

where F is the total energy output of a galaxy (luminosity of a galaxy) and f is the flux measured on the earth. Astronomers use magnitudes m to describe the flux measured on the earth; the relation between m and f is

$$m = -2.5 \log_{10} f + \text{constant}$$

Hence, a larger value of m means a smaller value of f. The measurement of the magnitude m is actually done at certain wavelengths (e.g., m_V is measured at a wavelength of 5500 Å, yellow light). On the other hand, because of red shift, the fluxes of different parts of the spectrum are measured and the bandwidth of the spectrum is also effected. Thus, a correction term must be added to the measured magnitude. If the measured magnitude is m_V, then the true magnitude $\overline{m}_V$ is related to m_V through the relation:

$$\overline{m}_V = m_V - k_r$$

k_r is the correction factor. Its value depends on the red shift. k_r is what often is referred to as the k-correction term. In actual work, $\log \frac{\Delta\lambda}{\lambda}$ is plotted against $\overline{m}_V = m_V - k_r$. If Hubble's law is valid then the resulting curve is a straight line, for galaxies having the same value of F (i.e., the same luminosity).

However, the variation in luminosity among galaxies is quite large. In addition, galaxies possess some random motions amounting to as much as 500 km/sec. Fortunately, this random motion becomes less important for distant galaxies which possess a high velocity. In reality, when log $\frac{\Delta\lambda}{\lambda}$ is plotted against $m_v - k_r$, a statistical distribution of points around the theoretical line

$$\log \frac{\Delta\lambda}{\lambda} = 0.2\ (m_v - k_r) + \text{constant}$$

will result (see Figure 1). In order to determine the shape of the observed line, one needs either (a) a large number of samples, or (b) types of galaxies which have similar luminosities. In other words, some standard candles are necessary.

Such standard candles were found by Sandage. He found that the brightest members of clusters of galaxies have roughly the same magnitude. The resulting curve of log $\frac{\Delta\lambda}{\lambda}$ versus $(m_v - k_r)$ is a straight line. This will be discussed later.

Are there other forms of matter in the Universe besides that found in galaxies, namely the so-called intergalactic matter? So far no intergalactic matter has been found. Some matter has been found between certain neighboring galaxies. However, there is no indication that such a phenomenon is universal.

If the red shift of quasars is cosmological in origin, then, from the shape of an emission line of hydrogen, the density of intergalactic neutral hydrogen cannot exceed 10^{-34} g/cm^3, according to Gunn and Peterson. However, the nature of the red shift of quasars is not known with certainty.

To summarize: the distribution of matter (in the form of galaxies) in the Universe appears to be isotropic as well as homogeneous, with a density of 3×10^{-31} g/cm^3.

Are there any other forms of matter or energy which have not been accounted for? To answer this question we must first examine the existing cosmological theories.

Cosmological Theories.

If all cosmological theories are excluded which contain speculations violating currently accepted physical laws, then only one type can be considered. This is the cosmology originally formulated by Friedmann, based on Einstein's theory of general relativity.

Why is Einstein's theory favored over others? Einstein's theory is based on one very important property of gravitation: the trajectories of particles in a gravitational field with the same initial velocities and positions are identical, independent of the constitution of matter. This is certainly not true for the electromagnetic field. (An electron will be repelled by the field of another electron while a positron will be attracted by it.) This property enables Einstein to treat the gravitational field as a geometrical property of space-time. Hence the theory of gravitation may be formulated by using geometrical theory, the one used being Riemannian geometry. Einstein's theory contains no additional constants. The gravitational constant in Einstein's theory is the same as that used in Newtonian theory. In other theories additional constants must appear (e.g., the scalar field theory). Einstein's theory also shows good agreement with the three or four tests of general relativity. It has been argued that these tests do not exclude other theories because of experimental inaccuracies. To me, a theory has a right to exist only after it is verified by experiments. Einstein's theory has been verified by observations, even though the verification is not very accurate. Other theories, e.g., the scalar theory, have not even been verified to any degree of accuracy. A theory should not be used simply because it fulfills a philosophical need. For this reason, I favor Einstein's theory over other theories.

For a theory as complicated as Einstein's (it contains ten equations plus a number of subsidiary conditions), one might expect a large choice of cosmological theories. Surprisingly, Einstein's theory gives only one type of cosmology, namely the cosmology of an evolving Universe. The assumption of isotropy and homogeneity discussed earlier has been invoked to arrive at this result. This cosmology was first worked out by A. Friedmann, a Russian physicist, in 1922.

The Einstein-Friedmann theory predicts that a Universe is in a constant state of motion. Let R be the scale length of our Universe (R may be regarded as the average distance between two neighboring galaxies or two conveniently chosen objects of reference). The solution found by Friedmann regarding the behavior of R is illustrated in Figure 3.

At a certain time the Universe originated with a zero radius, and subsequently expanded. The expansion could be a permanent one, in which case the Universe is said to possess a negative curvature, or to be an open universe. Alternatively, the expansion could slow down and be replaced by a contraction at some later time. Thereafter the Universe would contract until its radius equalled zero. This type of Universe is said to possess a positive curvature, or to be a closed Universe.

Certainly nothing can possess a zero radius in the real world; a zero radius would mean an infinite density — a premise not acceptable to most physicists. On the other hand, the general relativity theory is a classical theory — it is not applicable to atomic or sub-atomic phenomena. The effects of atomic phenomena in a gravitational field can be studied only when the gravitational field is sufficiently weak, i.e., when the variation of the gravitational field over atomic or nuclear dimensions (10^{-8} cm or 10^{-13} cm respectively) is small. This condition is fulfilled. However, in the early stages of the evolution of our Universe, when the density was too great the gravitational field would enter into the quantum region. At present, no successful quantum theory of gravitation has been developed — and no solution is in sight. Hence, we do not know how the Universe behaves near the point of R = 0.

If we are not concerned with what happens near R = 0, then much can be said about the evolution of our Universe. After roughly 10^{-6} sec, the gravitational field will have become classical; that is, the variation of the gravitational field over an atomic or nuclear dimension becomes small. The density of the Universe becomes comparable to the density of a nucleus, 10^{14} g/cm^3. This is a very high density, but the property of matter at this density is known through the study of the properties of nuclei.

What makes a Universe open or closed? This is determined by the matter-energy density. With the present value of Hubble's constant, the Universe is closed if the density exceeds 3×10^{-29} g/cm^3; otherwise it is open. The present density of matter in galaxies is 3×10^{-31} g/cm^3. Does this mean that the Universe is open? We must remember that matter-energy can also exist in other forms. We shall draw a tentative conclusion later, after studying the physics of the Universe.

One final word may be said about the characteristics of open and closed models. In a closed Universe the total amount of matter-energy is finite. The Universe expands from a zero radius, and then starts to contract after reaching a maximum radius, eventually returning to zero radius. What happens afterwards is not known, or at least not clear from Einstein's theory. The closed model is sometimes called an oscillatory model because some relativists believe that a closed model can be continued by adding another closed model after a zero radius has been reached. Hopefully, the Universe will undergo expansion and contraction over and over again. As far as is known, within the framework of Einstein's theory of gravitation, expansion and contraction will occur only once. It may be argued that since Einstein's theory should not be valid at the origin of the Universe, perhaps an unknown mechanism will cause the Universe to reverse its direction of motion when it contracts to a critical radius. However, no known physical mechanism can achieve oscillation and it is premature to speculate some "perhaps" mechanism.

In contrast, an open Universe expands forever. When the last star has consumed all its nuclear energy, the Universe will be in total darkness. It will be dead, but still expanding. There are certain theoretical difficulties associated with this model. The main difficulty lies in the fact that the total energy of such a Universe is not defined; when all the energy is added up, one gets an absurd result: the energy is infinite. However, this difficulty originates from the fact that the Universe has an infinite volume. Why should our Universe extend to infinity? It appears more natural that our Universe should end somewhere; but so far, this difficulty has not been resolved.

Summarizing: Einstein's theory of gravitation permits only one type of cosmology; namely, that in which the Universe originates from a singularity — literally, a point. This type of cosmology has been commonly called the big bang theory. There are two alternatives within the big bang theory: in the closed model, the Universe expands to a maximum radius and then contraction takes place; in the open model, the Universe expands forever.

Physics of Cosmology

The model furnished by Friedmann based on Einstein's theory provides a good starting point. Admittedly it is a highly theorized model in which particle interaction and inhomogeneities are neglected. The Einstein equations could be modified to include particle interactions and inhomogeneities; but this would result in an even larger number of equations, and hence be more difficult to solve. Alternatively, we can take the relatively simple Friedmann solutions as they stand, and treat particle interactions as small disturbances. This alternative approach gives a result very closely resembling that which would have been obtained from the set of more complicated relations.

Figure 4 shows the schematics of the evolution of matter in the Universe. This chart can be called the "organization chart of our Universe." As was stated earlier, the matter-density of the Universe was very high in the early epoch; 10^{-6} seconds after the Universe was created, the density was of the order of 10^{14} g/cm^3, which is the nuclear density. The temperature was also very high, approximately 10^{13} °K. At this temperature and density, the composition of matter is quite complicated. Even protons are not stable: they can undergo reactions which convert them into other fundamental particles. Even antiprotons and antineutrons are created. The energy density of neutrinos is also high, being comparable to the energy density of radiation.

As the Universe expands, matter and radiation cool down. When the temperature drops to 10^{10} °K, virtually all strange particles and antiparticles (except positrons) have disappeared. Remaining are protons, electrons, positrons, neutrons, and neutrinos.

Because of the nature of particle-antiparticle interactions, it is not possible for particles to separate from antiparticles, assuming thermodynamic equilibrium. Einstein's theory of gravitation, the existence of particle-antiparticle interaction, and the recognized physics laws prohibit the coexistence of particles and antiparticles in the Universe. In other words, Einstein-Friedmann cosmology excludes the existence of anti-galaxies (galaxies composed of antimatter). The present dominance of particle population over antiparticle must have been a property of our Universe; this property existed when it was created. The existence of an antigalaxy or anti-star is inconsistent with Einstein-Friedmann cosmology, if one accepts the present form of laws of physics.

When the temperature drops to 10^9 °K, a large fraction of electrons and all positrons are also annihilated, enriching the energy of radiation. The composition of matter at this temperature is protons, neutrons, electrons, radiation, and neutrinos. The latter (which also include antineutrinos), however, play a very negligible role in the further course of evolution.

Between a temperature of 10^9 °K to a few times 10^8 °K, a buildup of elements from protons and neutrons takes place. At higher temperatures, nuclei are unstable and they will break up as soon as they are formed; at lower temperatures, the nuclear reactions are too slow against the expansion time of the Universe. The temperature range of 10^9 °K to a few times 10^8 °K is just right for the buildup of elements. The time the Universe spends in this temperature range is about 1000 seconds.

The process by which the main elements are built up are as follows:

$$p + n \rightarrow D$$

$$D + p \rightarrow He^3$$

$$He^3 + n \rightarrow He^4$$

The neutron capture process ends up at Helium 4, because there is no element with a mass number of 5. A small fraction of heavier elements can be built up by another process however, but these processes are never very important. Altogether, in the first half-hour of evolution of our Universe, approximately 20% of the protons are converted into helium.

The relationship between the temperature of radiation and the scale length R is

$$\text{Temperature of radiation} \propto R^{-1}$$

and that for matter is

$$\text{Temperature of matter} \propto R^{-2}$$

Hence matter cools down faster than radiation. However, in reality, the temperature of matter is very close to the temperature of radiation, because collision processes of the type

$$\gamma + e^- \rightarrow \gamma + e^- \text{ (electron scattering)}$$

continually transfer energy from photons to matter to raise its temperature. However, when the temperature falls below 10^6 °K, the process that efficiently transfers energy from photons to matter is the photoionization process in which the atomic electron is set free by absorbing a photon.

The photoionization process, however, tends to remove energy from the shorter wavelength part of radiation, because there is a threshold involved, as illustrated in Figure 5.

The photoionization process will distort the radiation spectrum, but the effect is very small because the energy density of radiation is tens of thousands times greater than the energy density due to matter. The law of decrease of radiation energy density due to expansion is

$$\text{radiation energy density} \propto R^{-4}$$

$$\text{matter energy density} \propto R^{-3} \quad .$$

Hence, at an earlier time, radiation energy dominated.

When the temperature falls below a few times 10^3 °K, electrons and ions will have almost completely recombined, leaving only a trace amount of matter (10^{-3} to 10^{-4} of all matter) frozen in the ionized state until galactic formation.

As long as the radiation energy density exceeds the matter energy density, gravitational condensation of gas masses into galaxies and stars cannot take place. This is because radiation is a "light" gas; it has too little energy for the pressure it generates. Its pressure is far too great for the self gravitational attraction required to hold it together. Because of the law of decrease of energy density due to expansion of the Universe, radiation energy density eventually becomes less than matter energy density. After this stage, galactic formation can take place. The temperature corresponding to an equal radiation density to matter density is around room temperature, namely 300 °K.

The condition for gravitational condensation at a given temperature and density involves a certain scale length. Gravitational condensation will take place if the dimension involved exceeds this scale length. The scale length involved at a temperature of 300 °K is in the neighborhood of 10^{21} cm, containing a mass of the order of 10^{39} grams. These values are too small to account for the mass of most galaxies, but they imply that objects of a mass smaller than 10^5 solar masses cannot be condensed in the intergalactic medium. The smallest galaxy observed has a mass close to 10^5 solar masses.

From dimension analysis we may conclude that the hierarchy of gravitational condensation is: clusters of galaxies, then galaxies, star clusters, stars, planets, rocks, etc. We can therefore rule out the existence of rocks, or small invisible matter in intergalactic space.

Once galaxies exist, stars are formed next. The observed mass of stars range from 0.1 solar mass to 60 solar masses. The nuclear energy content of a star is roughly a few tenths of one percent of its rest energy, and the luminosity of stars is roughly proportional to the third power of its mass. Thus, the life span of massive stars is considerably shorter than that of less massive stars. The lifetime of a 60 solar mass star is of the order of one million years, but the life span of a star of 0.8 solar mass is nearly 20 billion years. Since the projected age of the Universe is 10^{10} years, we may find in some of these oldest stars the primordial matter that was manufactured in the first half hour of the Universe. Such stars should contain nearly 20% helium, and none of the heavier elements such as iron and carbon.

We know that heavy elements are formed in the stars. When stars become supernovae or exploding stars, these elements are ejected into space. Interstellar gas thus becomes enriched with heavy elements, and younger stars should have a higher heavy element content than older stars. Indeed, stars can be classified into two populations: Population I stars, populating the spiral arm of a galaxy; and Population II stars, populating the nucleus and the large halo region of a galaxy (Figure 6). The heavy element content of Population I stars is about 3%, but for Population II stars it is much less than 1% — and in certain cases no spectral lines containing heavy elements are formed.

At present, the primordial radiation which was once hotter than all the nuclear fires combined, has finally cooled to a temperature of 3 °K. How do we detect this radiation? This question will be answered below.

Observational Tests of Cosmological Theories.

We are now in a position to test theories of cosmology by experiments and observations. There are two types of tests. The first tests the geometrical structure of space-time associated with our Universe; in other words, one tries to observe the curvature of our Universe. In the other, one tries to observe the physical phenomena associated with the Universe, such as those discussed in the preceding section.

Large-Scale Structure of our Universe.

As was stated previously, in Einstein-Friedmann cosmology the large scale structure of the Universe is characterized by a knowledge of the scale length R as a function of the time t. There are two parameters which characterize a model; the first of these is the Hubble constant H_o, which is also the fractional expansion rate:

$$H_o = \frac{1}{R}\frac{dR}{dt}$$

The second is the deceleration parameter, which characterizes the deceleration of expansion (note that in the R versus t curve (Figure 3) the curve indicates deceleration). A large value of q_o means a more strongly decelerated Universe.

The sign of the curvature of the Universe (or the openness or closedness of a particular model) is determined by the value of q_o; for a Universe whose constituent is predominantly matter (like our own), if the value of q_o exceeds 0.5 then the sign of the curvature is positive (closed Universe; if the value of q_o is below 0.5, then the sign of the curvature is negative (open Universe). In all cases the value of q_o is proportional to the density, its value is

$$q_o = \frac{\text{matter density}}{3.21 \times 10^{-29}\ \text{g/cm}^3}\left(\frac{100\ \text{km/sec/megaparsec}}{H_o}\right)^2 .$$

For a Universe whose constituent is predominantly radiation, the critical value for q_o is 1.0.

When distant galaxies are observed, we are not only looking into distant space, but also looking backward into time, because it takes time for light to reach us. This means that the effect of deceleration will be most important for the most distant galaxies. For nearby galaxies, only the effect of expansion can be determined; that is, Hubble's constant. This effect of deceleration shows up in several places:

1) The density of galaxies will be different if we look backwards in time; this is because in the past, the Universe was more closely packed.

2) The relation between the logarithm of red shift and the magnitude shows a non-linearity for distant galaxies.

3) The curvature effect will also show up in the relation between the apparent angular size of a galaxy and the red shift.

To illustrate this point, consider a two dimensional universe in the form of a sphere (see Figure 7). Light is constrained to travel along the great circles. It is clear that at first the angular size of an object is inversely proportional to the distance, but then the dependence becomes weaker and eventually the object reaches a minimum size at mid-point between the observer and the antipode, and the angular size increases beyond this mid-point.

One of the reasons for the construction of the 200-inch Mt. Palomar telescope was to study these problems. Unfortunately, after the telescope was put into use, astronomers discovered that they had underestimated the distance of distant galaxies by a factor of two. This also meant that a 200-inch telescope could not provide answers to the three questions unless some ingeneous method were used.

In Figure 1 we have clearly shown the theoretical predictions of log V versus $m_v - k_r$. Figure 8 shows the red shift—apparent magnitude relation for 39 identified radio sources. Clearly, no information on q_o is available.

In his work, Hubble discovered that the intrinsic magnitude of the brightest members of clusters of galaxies appears to be rather constant among the samples he has studied, in the sense that the observed curve of the logarithm of the red shift versus the magnitude (after correcting for red shift according to the actual spectrum) is linear with only a small scatter of data (to 0.2 magnitudes). Allan R. Sandage used this property to study the curvature of our Universe. His recent result (shown in Figure 9) shows that the the value of q_o is very close to unity but the error is still large—of the order of 50%. If this result is taken literally, then our Universe can be described by a closed model. (A word of caution here is not to be over enthusiastic about this number. The work is still being carried out by Sandage and his collaborator, J. Kristian. They are optimistic about their ability to obtain a more accurate value of the deceleration parameter q_o.)

Remnants of Creation

We can also examine more closely the remnants of creation — what our Universe has left us to study today. This approach has been taken up recently more vigorously than ever. What are the relics from creation? From what we have discussed, we see that we have the following to study:

1) The cosmic blackbody radiation. As was mentioned earlier, the primordial radiation, once hotter than all nuclear fires combined, has now cooled to an incredible three degrees above absolute zero. Can we detect it? The answer is yes, and indeed we have already detected at least a part of it.

Penzias and Wilson at Bell Telephone Laboratories undertook an experimental program to measure the microwave noise at 7 cm due to our atmosphere, in connection with the Echo Communications Satellite Project. The Penzias-Wilson apparatus consisted of an antenna pointing towards an arbitrary direction in the sky; slowly the antenna was directed towards zenith. One should expect that the noise due to atmosphere should decrease towards zenith. Indeed this was observed, but when they extrapolated their results to zero zenith height, Penzias and Wilson found a small amount of residual radiation corresponding to a blackbody radiation of 3 °K at this wavelength. When they communicated their findings to Robert H. Dicke, he was not in the least surprised; he had constructed a similar apparatus, but with the specific intent of searching for remnants of this primordial radiation. What Dicke, Penzias and Wilson did not realize was that Gamow and his associates had already predicted the existence of a blackbody radiation of a few degrees above the absolute zero some 14 years earlier. Their paper was forgotten in the course of time because they were too much ahead of their time.

According to a recent calculation, the deviation of the cosmic radiation from the blackbody radiation should be exceedingly small — around one part in 10^6 for our Universe. For all practical purposes the spectrum may be taken to be that of a blackbody. To date, about 10 points have been measured, all in good agreement with a cosmic blackbody radiation at a temperature of 2.7 °K, as shown in Figure 10. If this radiation is really cosmic in nature, it should be strictly isotropic. The isotropy of this radiation has been confirmed to an accuracy of 0.1%.

However, before one can accept the fact that this radiation is indeed the remnant of the primordial fire of creation, we must be critical about the interpretation of observational results. Penzias and Wilson's original findings were accepted as the cosmic radiation because there was no other interpretation available. Further, only the low frequency spectrum is available (below the maximum in the Planck distribution curve). We would be more comfortable if a point in the high frequency spectrum after the Planckian maximum were available. The maximum occurs at around .9 mm wavelength. Unfortunately below a wavelength of three mm., the atmosphere is a strong absorber of electromagnetic radiation; hence, this problem can only be solved by performing experiments above the atmosphere. At present there are few points available from interstellar molecular absorption (such as CN, CH and OH) line strengths in stellar spectra, but their interpretation is more difficult.

Even with this precaution in mind, I personally believe that the nature of the cosmic radiation is well explained as the remnant of the fire of creation.

2) According to cosmological theory, the helium content of matter one hour after creation until star formation is between 20-30%. If helium lines can be found in the oldest stars then we will be able to demonstrate that the temperature of the Universe was once as high as 10^9 °K.

The type of stars for which we are looking are Population II stars, which are old stars. However, their surface temperatures are quite low (in the neighborhood of 3000 °K or lower); helium lines can be excited only in the hottest stars (with a surface temperature of 10^4 or greater). Hence in ordinary Population II stars the presence of helium cannot be detected. Helium lines have been detected in some Population II stars which have evolved away from the main sequence and have a higher temperature, but the exact helium content is not known.

The two tests described above are the most important which are currently being carried out in a number of laboratories and observatories. Are there other possible tests? Yes; however, they are even more difficult to carry out. For example:

1) The Einstein-Friedmann cosmology predicts no antiparticles in the Universe. Thus far, no antiparticles have been detected in cosmic rays. However, the experimental upper limit for antiproton flux is far from satisfactory for this kind of work.

2) According to the Einstein-Friedmann cosmology, there should be at most a small amount of ionized gas in intergalactic space. No experimental upper limit or lower limit is available.

3) The neutrino and antineutrinos should also have a black-body spectrum with a slightly lower temperature (~ 2.2 °K). However, the detection of such neutrinos is beyond even the realm of theoretical possibility.

<u>One Major Difficulty with the Present Cosmology: Stellar Age</u>.

Despite the measure of success in Einstein-Friedmann cosmology, there are still some serious difficulties. The most prominent is the inconsistency between the age of the oldest stars in our Galaxy and the age of the Universe. Stars can be dated by using accurate stellar models and the observed H-R diagram, which is a plot of stellar luminosity against their surface temperature (Figure 11). In this plot, 90% of the stars fall into a diagonal strip called the main sequence. The theory of stellar evolution tells us that after a certain fraction of stellar nuclear energy is consumed, stars evolve away from the main sequence to the red giant region (characterized by high luminosity and low surface temperature) (see Figure 9). The time when stars evolve away from the main sequence is strongly dependent on their mass, but practically independent of the chemical composition. According to Sandage the age of the star cluster NGC 188 is $(1.5 \pm 0.2) \times 10^{10}$ years.

The age of the Universe may be obtained once the present value of H_o and q_o are known. In general the age is less than the Hubble age which is $1/H_o$. For our Universe this is 1.3×10^{10} years. If the matter density is nearly zero and R increases linearly with t, then the age is $1/H_o$. However, if the matter density is not zero, then the Universe has decelerated during its expansion and $1/H_o$ is greater than the actual age of our Universe. If the value of q_o is unity, then the actual age of our Universe is only 8 or 9 billion years — much too small to account for the existence of those old star clusters. A barely acceptable premise is to admit that the energy density of our Universe is the energy density of galaxies, namely 3×10^{-31} g/cm^3. This will give a very small value of q_o ; the age of the Universe and H_o^{-1} will nearly coincide.

APPENDIX

A Brief History of Einstein-Friedman Cosmology

Year	Name	Event
1905	Albert Einstein	Theory of special relativity formulated.
1915	Albert Einstein	Theory of general relativity formulated.
1916	Karl Schwarzschild	Obtained the field solution to a spherical mass distribution.
	Albert Einstein	Explained the advancement of the perihelion of Mercury. Predicted the bending of light around the sun.
1917	Albert Einstein	Failed to produce a static cosmology. Introduced an arbitrary constant called cosmological constant to force his cosmology to be a static one.
1918	Arthur Eddington	Confirms the bending of star light around the sun during solar eclipse.
1922	A. Friedmann	Obtained a dynamical solution in which the Universe is forever in a state of motion. This is the birth of the big bang theory which is the central theme of this paper.
1905-1925	V. M. Slipher G. Stromberg	Obtained the red shift velocity of a number of nebulae; found that the velocities of some of them range to 1000 km/sec.
1928	G. Hale	Promoted the construction of the 200" telescope in Mt. Palomar. Funds were provided by the Rockefeller Foundation.

(continued)

History of Einstein-Friedman Cosmology (Cont'd.)

Year	Name	Event
1929	E. Hubble	Definitely confirmed Slipher and Stromberg's findings; in addition Hubble showed that the expansion rate of increases linearly with the distance. Expanding universe is thus accepted. The expansion rate constant is called the Hubble's constant.
1931	G. Lemaitre	Further studied cosmological models; laid down the foundation of the big bang theory.
1934		200" mirror blank was cast in Corning, New York.
1945	R. H. Dicke	Invented the first radiometer.
1948		Dedication of the 200" telescope which is named after Hale.
1950		The first discovery made on the 200" telescope: the distance scale used previously is too small by a factor of 2.
1953	G. Gamow R. A. Alpher R. C. Herman	Formulated the physical consequences of the big bang theory. Predicted 1) cosmic radiation background of the order of 5 °K, 2) 29% primordial helium in oldest stars. Their papers were entirely forgotten because they were too much ahead of time.
1964	R. H. Dicke	Did not read Gamow et al. papers. Rediscovered independently the cosmic blackbody radiation background.
	A. A. Penzias R. W. Wilson	Found a residual radio noise of a temperature of 3 °K at 7 cm unexpectedly when they were trying to improve communication by Echo Satellite. Used Dicke type radiometer.
1967		Radiation background temperature is 2.7 °K.
1968 and beyond		?

MEASUREMENTS OF COSMIC BLACKBODY RADIATION

as of November 1967

λ(cm)	T(°K)	Reference
0.26	2.7 - 3.6 (CN)	Field and Hitchcock, Ap. J. 146, 1 (1966), Phys. Rev. Ltrs. 16, 817 (1966).
	3.75 ± 0.5 (CN)	Thaddeus and Clauser, Phys. Rev. Ltrs. 16, 819 (1966).
	2.85 ± ? (CN)	Ibid, (reported at 3rd Texas Symposium Jan. 1967).
0.80	2.9 ± 0.7	Salmonovich (reported at IAU, 1967).
1.5	2.0 ± 0.8	Welch, et. al. Phys. Rev. Ltrs. 18, 1068 (1967).
1.58	$2.82 \pm {.12 \atop .17}$	Stokes, Partridge and Wilkinson, Phys. Rev. Ltrs. 19, 1199 (1967).
3.2	3.0 ± 0.5	Roll and Wilkinson, Phys. Rev. Ltrs. 16, 405 (1966).
	$2.70 \pm {.16 \atop .21}$	Stokes, Partridge and Wilkinson, Phys. Rev. Ltrs. 19, 1199 (1967).
7.35	3.5 ± 1.0	Penzias and Wilson, Ap. J. 142, 419 (1965).
20.7	2.8 ± 0.6	Howell and Shakeshaft, Nature 210, 1318 (1966).
21.0	3.2 ± 1.0	Penzias and Wilson (reported to AAS, Los Angeles, Dec. 1966).
49.2 to 73.5	2.5 ± 1.6 Avg.	Howell and Shakeshaft (reported at IAU, 1967).
Isotropy measurements:		Partridge and Wilkinson, Phys. Rev. Ltrs. 18, 557 (1967); Nature, Aug. 1967.
		Conklin and Bracewell, Phys. Rev. Ltrs. 18, 614 (1967); Preprint, Nov. 1967).
		Penzias and Wilson, Science, 156, 1100 (1967).

FIGURE CAPTIONS

Figure 1. Theoretical curve of the log CZ vs m_v-k_r relation, with some observational points. q_o is the deceleration parameter explained in the figure caption of Figure 3, and later in the text. At small values of log (1+Z) all curves coincide.

Figure 2. Actual photographic plate (real size) of the spectrum of a nearby galaxy NGC 2985 and an enlargement of the spectrum. The two dark lines are the calcium H and K lines found in stellar spectra. The two dark lines have been shifted with respect to laboratory standards shown on top and bottom of the spectrum. The receding velocity of this galaxy is 1300 km/sec.

Figure 3. Schematic diagram illustrating the behavoir of the scale length R in different Einstein-Friedmann cosmology. The curves 1,2,3,... denote a sequence of cosmological models of different deceleration parameter q_o in descending order (see text). The significance of q_o is explained later in the text. Curves 1,2,3 denote closed models with $q_o > 0.5$ for a universe whose predominant composition is matter (or $q_o > 1.0$ for a universe whose predominant composition is radiation), and curves 5,6,7 denote models with $q_o < 0.5$ for a matter universe (or $q_o < 1.0$ for a radiation Universe). The critical case $q_o = 0.5$

Figure 7. Schematic diagram illustrating the curvature effect on the apparent angular size of an object in a two dimensional Universe. Light is constrained to move along great circles. The apparent angular diameter of an object at points a,b,c,d, will be bounded by the geodesics 1,1; 2,2; 3,3; 4,4. The apparent angular diameter will first decrease from position a until it reaches a minimum at the half-way point c, where its apparent angular diameter is a minimum. Afterwards its angular size will increase. In practice red shift causes objects near the antipodal point to become invisible.

Figure 8. The red-shift-apparent magnitude relation for 39 identified radio sources. The open triangles are the quasi-stellar sources with known red-shifts plus 3C286 with an assumed red-shift of $z = 0.850$. $L_r > 2 \times 10^{40}$ erg/s.

Figure 9. The red-shift-apparent magnitude relation for the first ranked member of clusters. Closed circles represent photoelectric observations made either by Pettit or the author. The crosses are photographically determined schraffierkassette magnitudes discussed by HMS. The open circle with error bars is 3C295. The abscissa is the total V magnitude corrected for the K-dimming and galactic absorption.

is represented by the curve 4, in this case the expansion of the Universe gradually comes to a standstill. Note in all cases the expansion rate decreases in the course of time, and models with greatest deceleration (curve 1) have the highest value of q_o. Hence the name deceleration parameter.

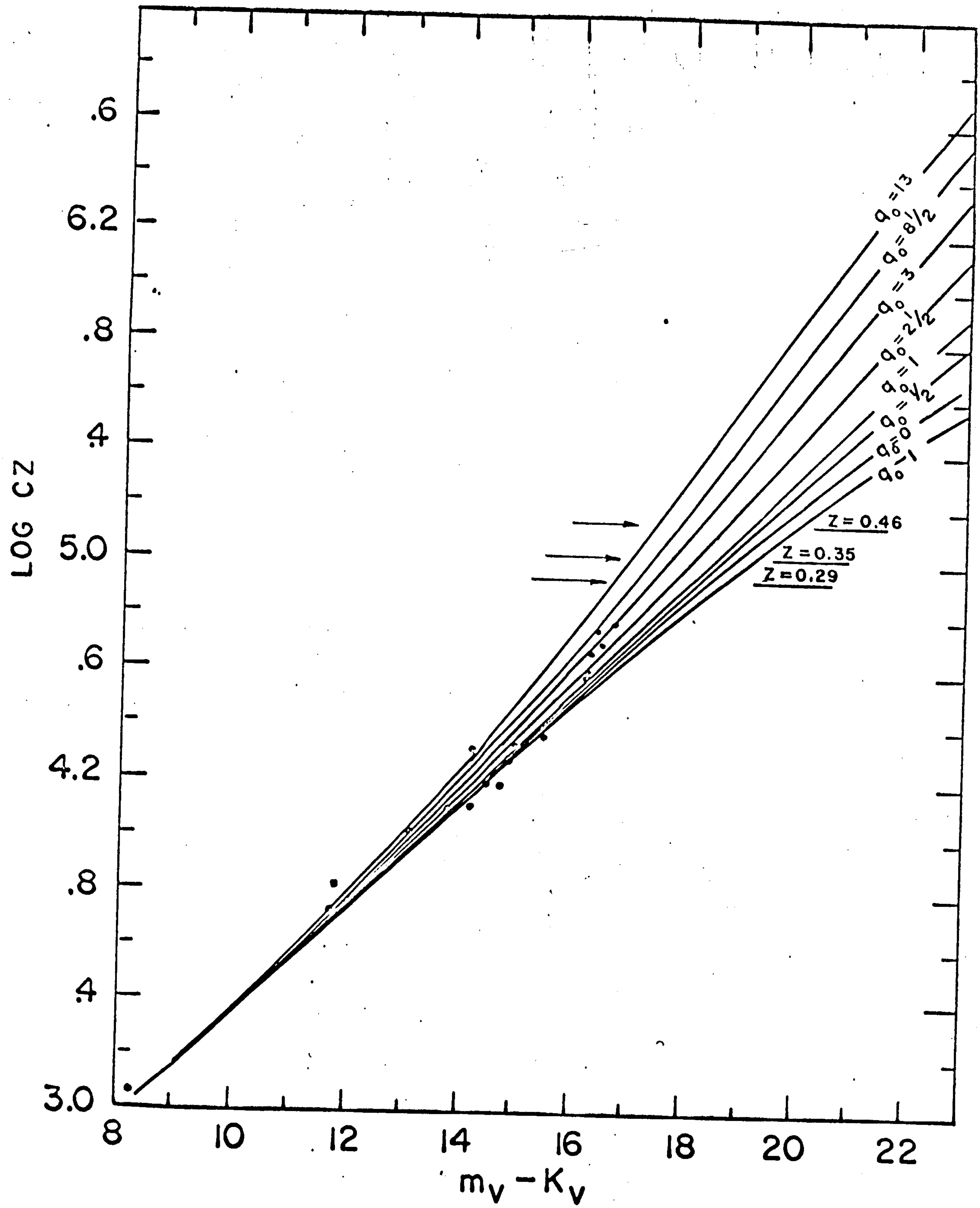
Figure 4. Schematic diagram indicating the relation between physical processes and the evolution of our Universe.

Figure 5. The evolution of blackbody radiation in our Universe as affected by hydrogen reionization. Curves 1,2,3,4 show the blackbody spectrum at four stages of the Universe in increasing time sequence. The temperature of the blackbody spectrum is decreased because of the expansion of our Universe. The threshold energy of photoionization of hydrogen is 13.6 eV and at a given time it affects only the part of a photon spectrum with energy greater than the threshold energy. Thus, only a part of the spectrum is affected and eventually when the bulk of the blackbody radiation is below the threshold (curve 4) the radiation spectrum is frozen until present. The temperature corresponding to the onset of freezing of radiation is around 6000 °K and the temperature of the present cosmic blackbody radiation is believed to be 2.7 °K.

Figure 6. Schematic structure of a galaxy (side view).

Figure 10. Cosmic noise background as of October 5, 1967. The numbers marked CN, CH, CH^+ are obtained from interstellar absorption lines in stellar spectra. (Courtesy of K. Thorne)

Figure 11. Comparison of the theoretical M_{bol} T_e diagrams for clusters of different ages with the observed diagram for M67 and NGC 188. The two dots represent δ Eri and μHer A. The numbers on the theoretical lines are the ages in 10^9 as unit. Hoyle's "type I" evolutionary track was used to obtain the theoretical diagram.



LOG CZ
.6
6.2
.8
.4
5.0
.6
4.2
.8
.4
3.0
8
10
12
14
16
18
20
22
$m_V - K_V$
$q_0 = 13$
$q_0 = 8\frac{1}{2}$
$q_0 = 3$
$q_0 = 2\frac{1}{2}$
$q_0 = 1$
$q_0 = \frac{1}{2}$
$q_0 = 0$
$q_0 = -1$
Z = 0.46
Z = 0.35
Z = 0.29

Fig. 1

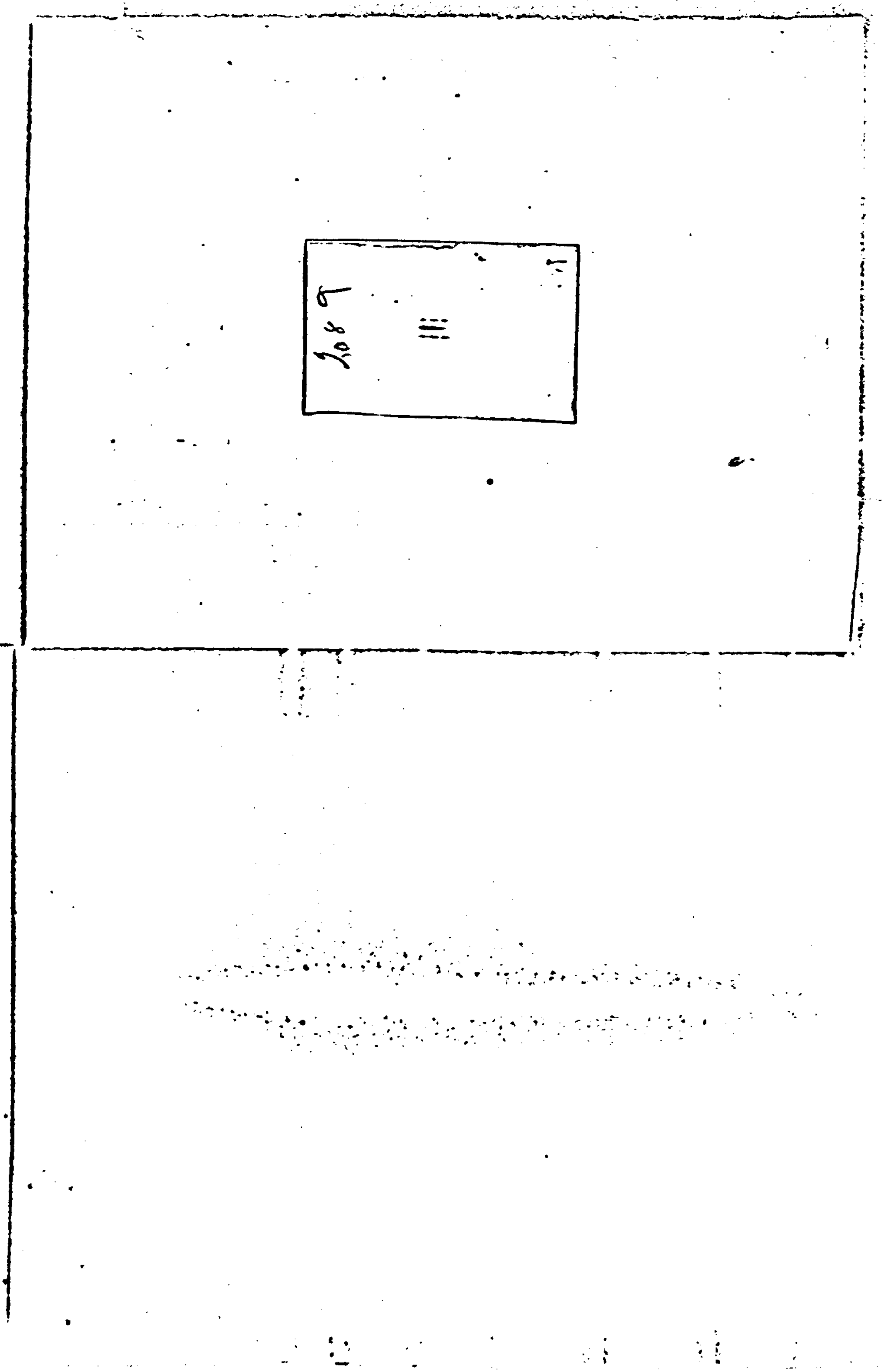


Figure 2.

NGC 2985 1300 km/sec

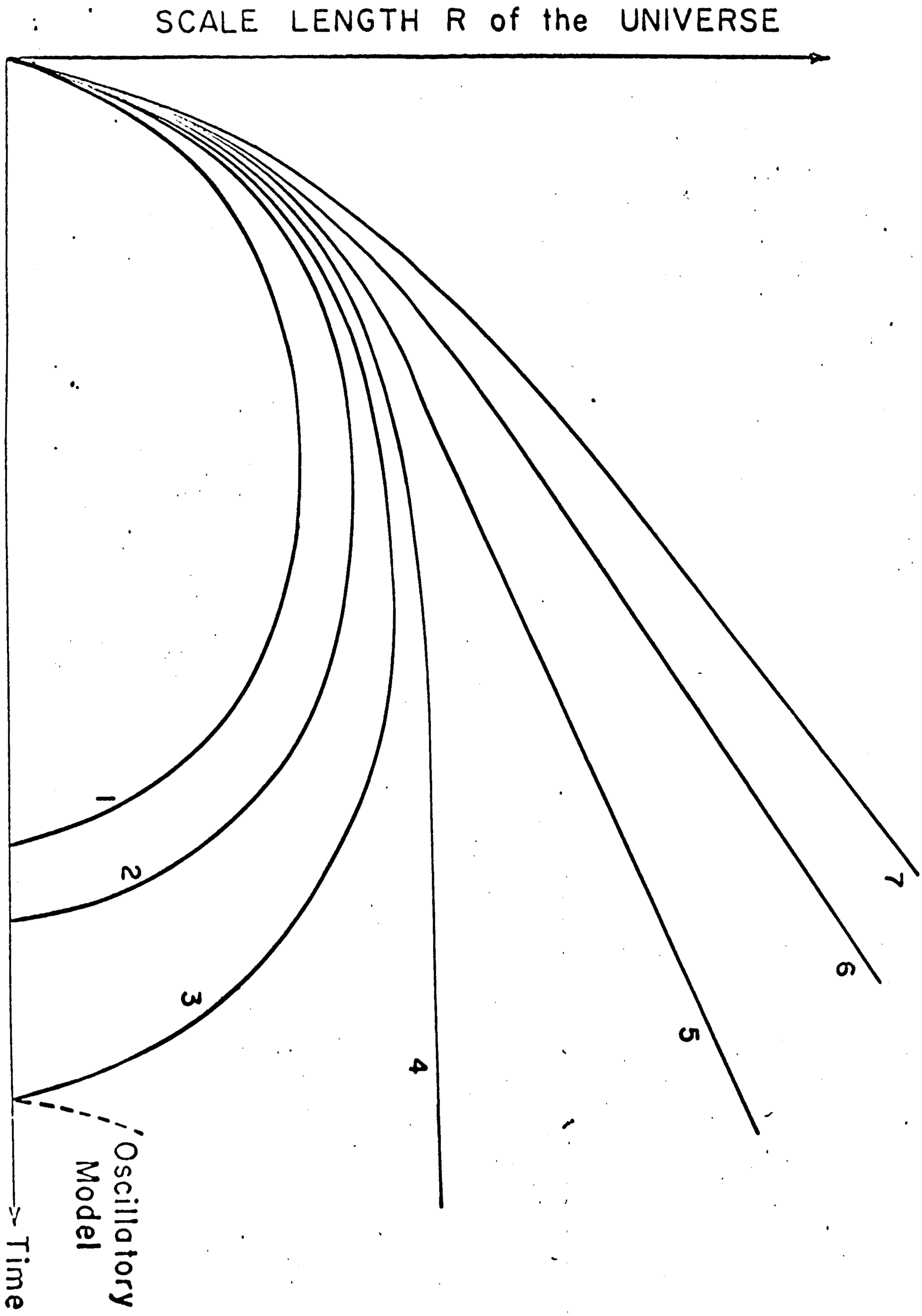
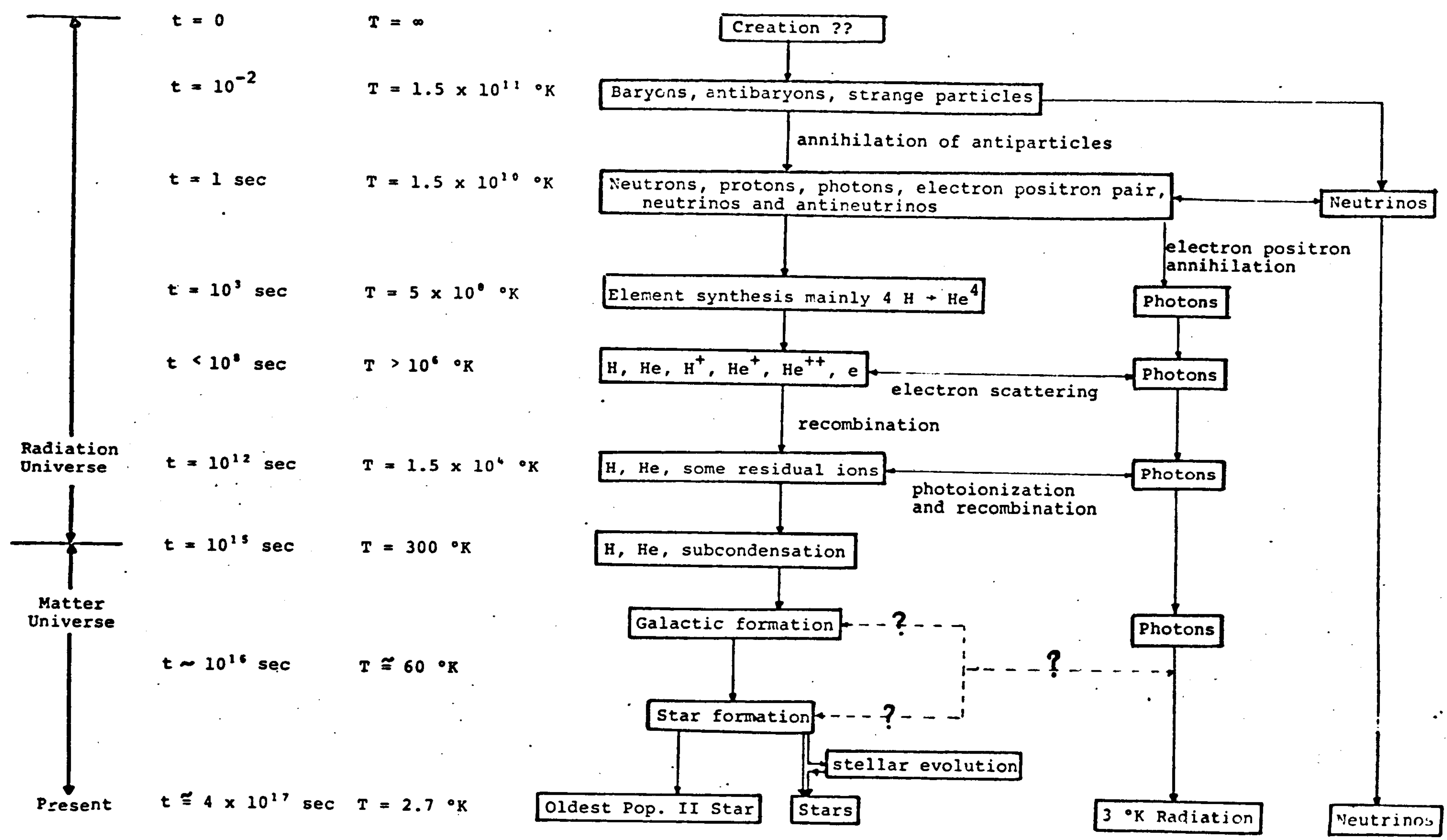

SCALE LENGTH R of the UNIVERSE
1
2
3
4
5
6
7
Oscillatory Model
Time

Fig.



t = 0
T = ∞
Creation ??
t = 10^-2
T = 1.5 x 10^11 °K
Baryons, antibaryons, strange particles
annihilation of antiparticles
t = 1 sec
T = 1.5 x 10^10 °K
Neutrons, protons, photons, electron positron pair, neutrinos and antineutrinos
Neutrinos
electron positron annihilation
t = 10^3 sec
T = 5 x 10^8 °K
Element synthesis mainly 4 H → He^4
Photons
t < 10^8 sec
T > 10^6 °K
H, He, H^+, He^+, He^++, e
electron scattering
Photons
recombination
Radiation Universe
t = 10^12 sec
T = 1.5 x 10^4 °K
H, He, some residual ions
photoionization and recombination
Photons
t = 10^15 sec
T = 300 °K
H, He, subcondensation
Matter Universe
Galactic formation
?
Photons
t ~ 10^16 sec
T ≅ 60 °K
?
Star formation
?
stellar evolution
Present
t ≅ 4 x 10^17 sec
T = 2.7 °K
Oldest Pop. II Star
Stars
3 °K Radiation
Neutrinos

Fig. 4

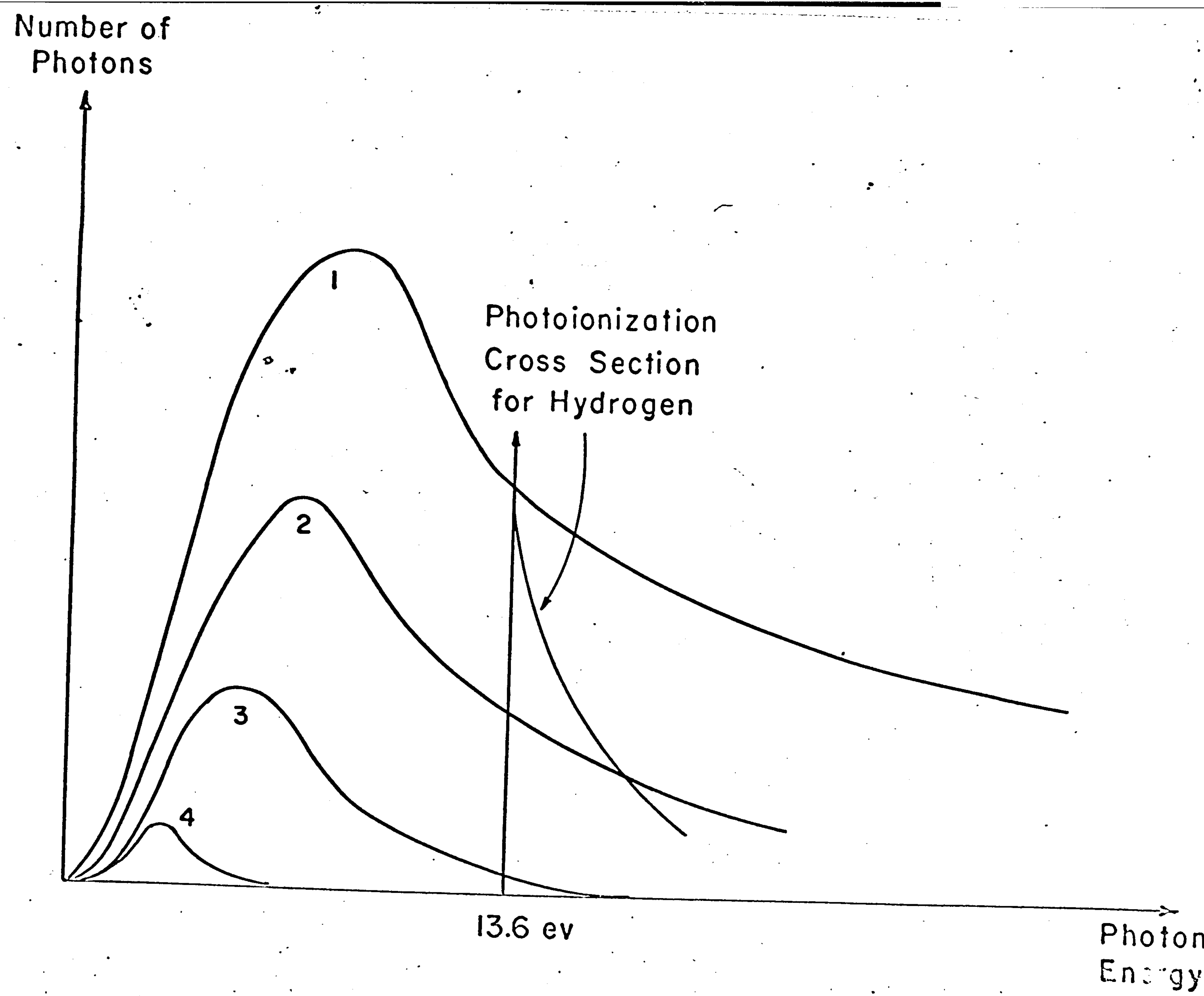
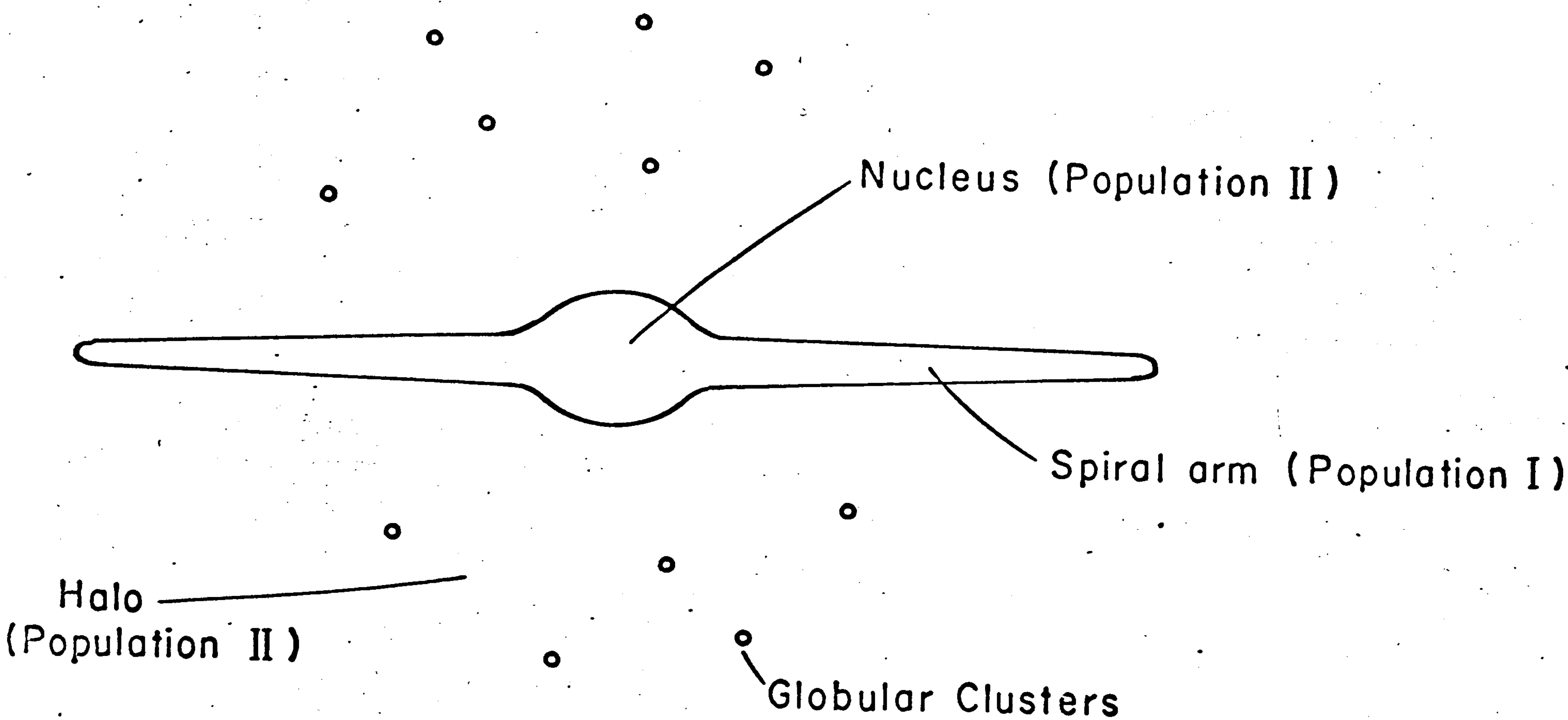

Number of Photons
1
2
3
4
Photoionization Cross Section for Hydrogen
13.6 ev
Photon Energy

Fig. 5

Fig. 6


Nucleus (Population II)
Spiral arm (Population I)
Halo
(Population II)
Globular Clusters

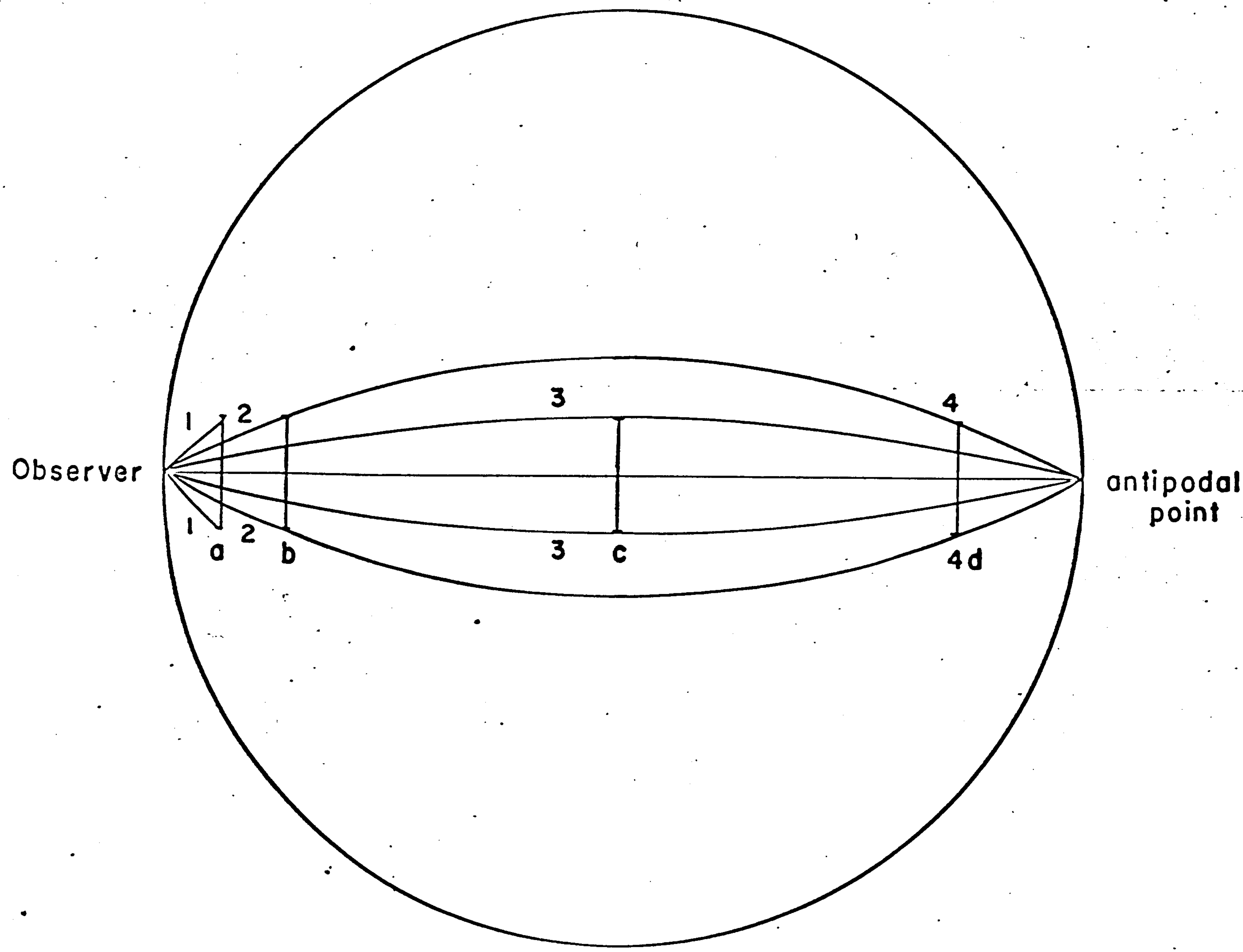


Fig. 7

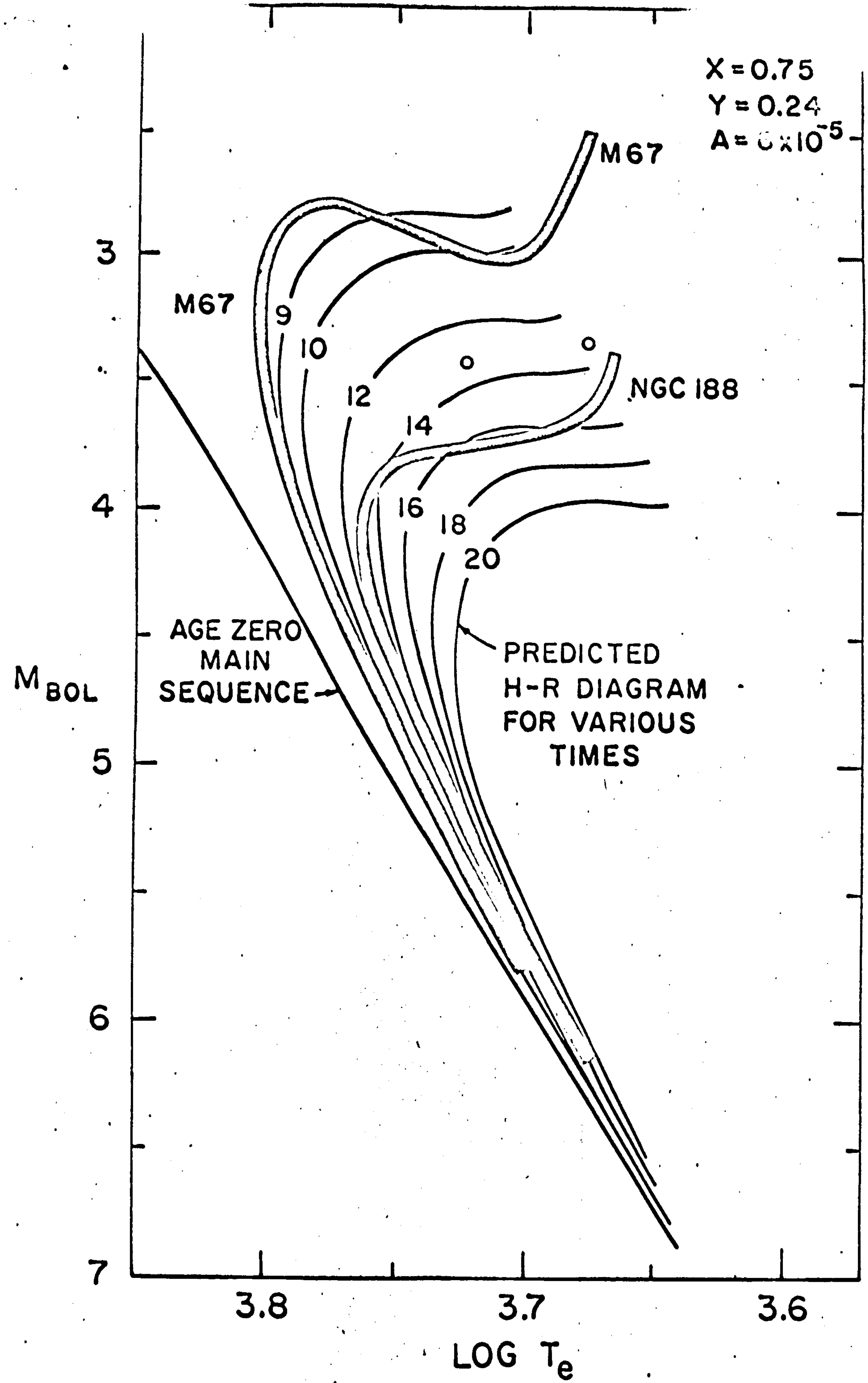
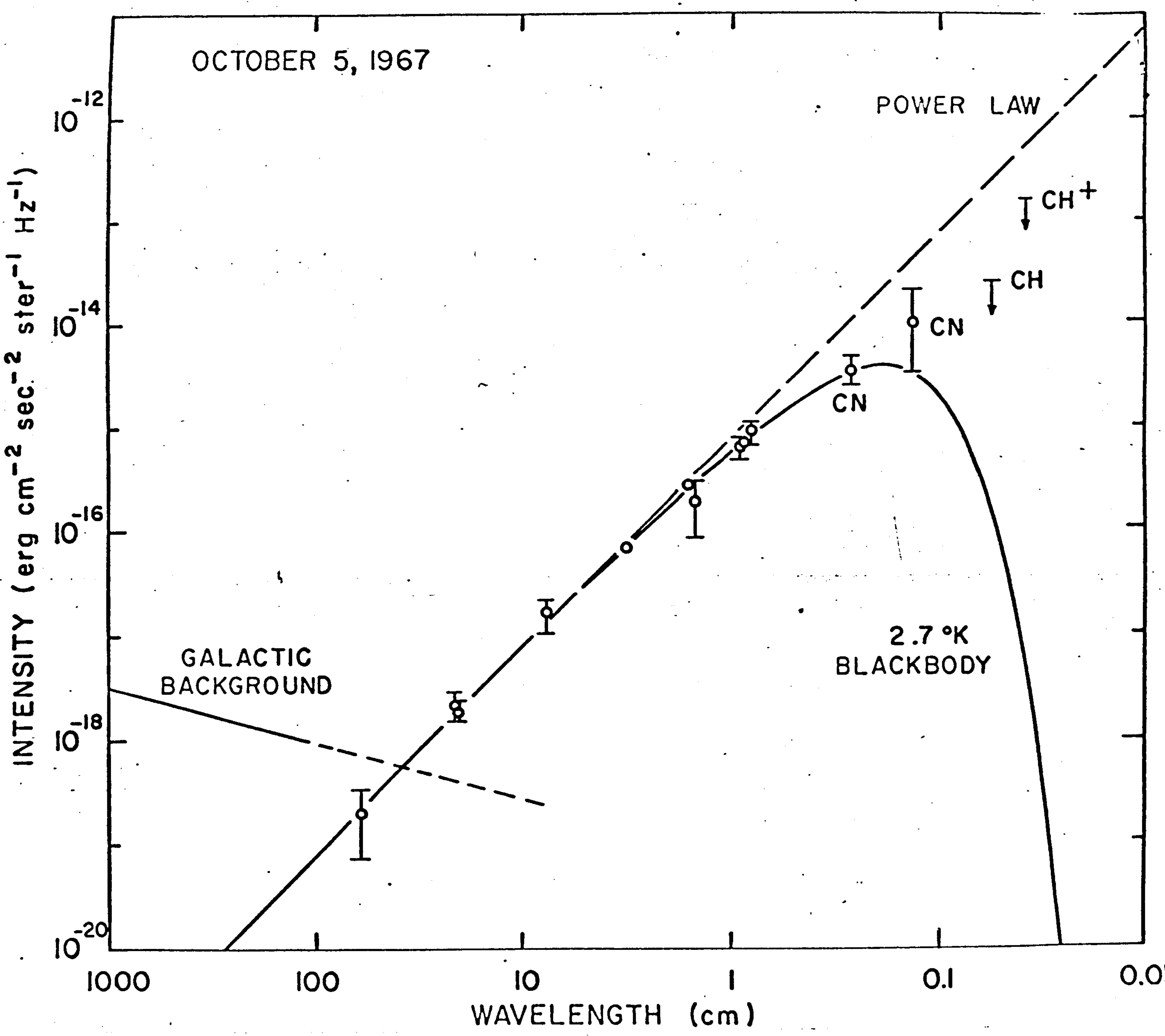

X = 0.75
Y = 0.24
A = 6x10-5
M67
M67
9
10
12
14
16
18
20
NGC 188
AGE ZERO
MAIN
SEQUENCE
PREDICTED
H-R DIAGRAM
FOR VARIOUS
TIMES
M BOL
3
4
5
6
7
3.8
3.7
3.6
LOG Te

Fig. 9



OCTOBER 5, 1967
POWER LAW
CH+
CH
CN
CN
2.7 °K
BLACKBODY
GALACTIC
BACKGROUND
INTENSITY (erg cm-2 sec-2 ster-1 Hz-1)
10-12
10-14
10-16
10-18
10-20
1000
100
10
1
0.1
0.01
WAVELENGTH (cm)